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Quantum device technologies - applying 2-D photonic crystals

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14. ABSTRACT
The project is focused on theory, fabrication and characterization of quantum information processing devices manipulating q-bits. Strong coupling between quantum dots and high-Q cavity was demonstrated, enabling both classical and quantum mechanical switching

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The Regents of the University of California, San Diego

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2. Objectives/Statement of work

1. Develop advanced rigorous electromagnetic and quantum mechanical modeling and design tools including electromagnetic time-domain finite element/difference and rigorous coupled-wave analysis (RCWA) necessary for design of linear and nonlinear nano-scale resonant structures.

2. Study near-field localization in 2-D photonic crystal nanocavities with quantum memory atoms, quantum dots, and their coupling structures. Investigate resonant nanostructured devices that utilize Electro-optic (EO) and nonlinear (NL) optical coupling. Study single and coupled quantum dots for quantum logic implementation.

3. Develop novel nanofabrication and characterization methods advancing e-beam and photolithography, quantum dot growth, near-field microscopy, and femtosecond time resolved imaging techniques.

3. Status of effort

1. An important theoretical insight to estimate the properties of nonlinear properties of various quantum systems has been established (see Table 1) to guide the experimental research in terms of quality of the cavity, mode volume, and coupling strength. The most important challenge was to define high-Q optical cavities with very small mode volumes, into which rare earth atoms can be introduced. It is clear that very high Q cavities have to be defined to overcome the rather small dipoles of the f-f transitions in rare earth doped crystals (see Table 1). Lower Q resonators could be used for strong coupling experiments for quantum dots, which have a larger optical cross-section, but a much shorter radiation lifetime.

System	Size	Dipole (eA)	Rad time	T2	Op time
Fluctuation quantum dot	300A	20	50 ps	100 ps	0.1 ps
Self-Assem quantum dot	30A	5	1 ns	100ps(?)	0.1 ps
Unit cell of bulk crystal	3A	5	5 ns	100 ps	N/A
Rare-earth in crystal	1A	0.01(f-f)	1 ms (f-f)	2 ms	?
Free atom	1A	1	30 ns (Cs)	60 ns	10 fm

Table 1. Comparison of different atom-like quantum systems

2. In order to assess the capability of a quantum dot (QD) cavity system as a compact replacement for the nonlinear Kerr medium for optical quantum information processing, we completed a theoretical study on nonlinear phase shift in the system with a QD embedded in a two-side cavity from the weak-coupling regime to the strong-coupling regime [1]. Fig.1 shows the phase shift for a coherent pulse light which contains one photon on average for a InAs dot as a function cavity Q factor and the exciton-cavity coupling g. The value of g=0.1 meV is now achieved by our

collaboration team [Scherer Nature article]. For equivalent phase shift, the length of the Kerr medium with the best nonlinearity would be of the order of one meter.

3. We have shown how a fundamental node (Fig. 2) can be built with a coupled system of a quantum dot, cavity and wave guide, based on our theory of the quantum electrodynamics of the excited state (trion) of a spin qubit in the dot interacting with the cavity photon which is coupled to the photon wavepacket in the wave guide. The optical process involves laser control of the trion of the dot and the output or input of the wavepacket via the wave guide. The node and wave guide may be formed into a quantum net [3], or be used for distributed quantum computing [4], or used to enhance photon-photon interaction such as in a phase gate [2].
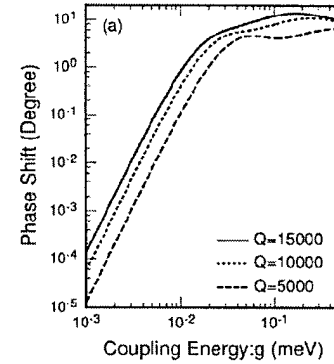

Fig. 1.   Nonlinear phase shift in a cavity containing QD as a function of g and Q

4. For operation with guided modes we have developed new cavity designs based on partial edge dislocations, in which the out of plane losses from the photonic crystal cavity are significantly reduced. Since the Q of the optical nanocavities are typically dominated by these out of plane losses, our new designs have allowed us to design cavities with Q values in excess of 10,000. For strong interaction between the optical field in the cavity and the atomic emitter, the field intensity also has to be designed to be maximum at the emitter position. If rare earth impurities in a low index matrix are to be used within high Q photonic crystal cavities, it is also important to define geometries in which there is a such a strong modal overlap. We are presently measuring the
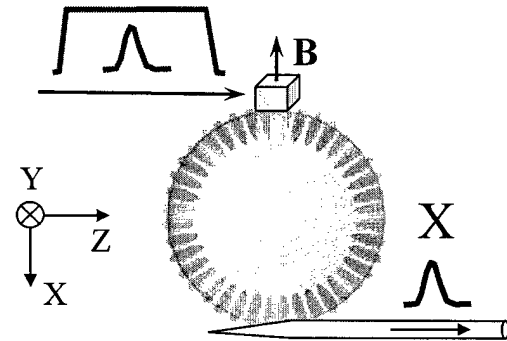

Fig. 2. A coupled system of quantum dot, cavity and wave guide, illustrating how optical pulse control can lead to emission of a single photon wave packet.

real Q values in these new high-Q designs by using quantum dot light emitting photonic crystal slabs. We conducted experiments using nanocavity with a substantially higher Q value than our initial photonic crystal cavities which were fabricated several years ago. The dependence of the Q on the stretching factor p is completely in agreement with the modeling results, and we believe that Q values higher than 2800 will be achievable as the optical cavities are fabricated with greater accuracy. Furthermore, optical cavities with very high Qs are expected to lead to low-threshold lasers which offer the opportunity for being electrically pumped. The confirmation of the performance of our high-Q designs also provides us with greater confidence in our optical modeling tools.

5. We have selected quantum dot emitters, self-assembled InAs islands in a GaAs layer, as the materials system of choice for an initial demonstration of strong coupling between a cavity and a narrow spectral light emitter. We measured the luminescence response before and after defining the optical cavity. We have defined photonic crystal

cavities with approximately 500 quantum dots in the optical cavity. We are presently examining these cavities with time-resolved measurements, with the hope of experimentally showing a change in the photon lifetime of the quantum dot emitters. These time-resolved measurements, conducted with a tuneable femtosecond OPO-based laser, are expected to provide the first experimental demonstration of strong coupling in photonic crystal based devices, and will yield to interesting optical devices. In order to characterize the quantum dot samples with both time and spatial resolution, we have purchased a scanning near-field optical microscope, which allows accurate positioning of the pump and/or probe beam used in time-resolved luminescence.

6. Our high Q optical resonator designs are ideally suited for interaction with atoms, either in vacuum or in the form of rare earth emitters in a dielectric material. One of the goals of this program is to determine the limits of the quality factor of such nanocavities. Typically, when such cavities are constructed in light-emitting material, there is significant re-absorption of light generated in the cavity by the lithographically patterned mirrors material surrounding the cavity. To explore the limits of the quality factors achievable in high-Q cavities, it is desirable to use completely transparent material. Silicon on insulator (SOI) offers a suitable materials system to ensure high transparency, as well as high refractive index contrast, in the telecommunication wavelength range of 1.3-1.6 micrometers. We have designed, fabricated and measured optical cavities in silicon to determine the spectral filtering characteristics, but unfortunately have not been able to successfully couple light into our smallest (and most interesting) optical cavities. So far, optical back-scattering measurements could only be conducted on larger cavities,

Fig. 3 Photonic crystal nanocavity (a) schematic of the nanocavity, (b) SEM of a fabricated nanocavity, (c) magnitude of the computed opticalfield superimposed on the nanocavity structure

and relatively high Q values of a few thousand could be observed in hexagonal ring structures. To enable local measurements, we are again using our near field optical microscope which can be pumped with our femtosecond time-resolved laser system in order to characterize such optical nanocavities. We have also developed very efficient coupler designs which allow light to be coupled from a fiber into SOI slabs with over 90% efficiency.

7. Recently, Caltech group has fabricated cavities with Q of 14,000 and used these designes to investigate QED systems. The experiments use GaAs for growth of quantum dots, whereas the confinement is achieved by making a 2-D triangular lattice photonic crystals with defects as shown in Fig. 3. Photoluminescence (PL) measurements were performed in temperature controlled liquid helium for few nanocavity devices as summarized in Fig. 4.
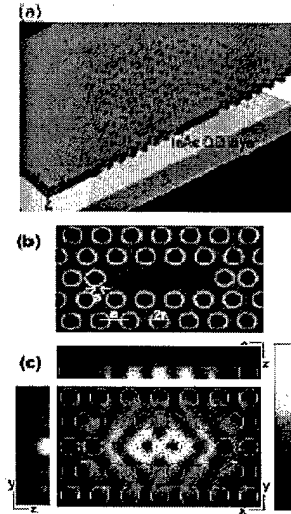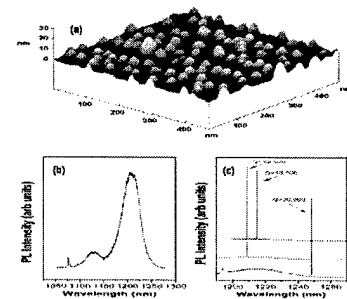

Fig. 4 Quantum dots and cavity modes (a) AFM profile of Quantum Dots without layers above (dot size 25 nm) (b)Ensemble PL for high excitation power (c) PL from the 3 nanocavities with the highest Q's

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The experiments in Fig. 5 a-c show that the nanocavity mode shifts much slower with temperature than the QD transitions and that the latter are much more visible at lower excitation powers. Therefore a quantum dot transition can be temperature scanned through the cavity resonance as shown in Fig. 5c. Experimental characterization of quantum dots in a photonic crystal nanocavity show anti-crossing behaviour, characteristic of strong coupling between quantum dot and high-Q cavity Strong coupling between quantum dot and high-Q cavity enables both classical and quantum-mechanical switching.

8. We investigate near-field interactions in optical nanostructures for the enhancement of nonlinear optical phenomena. In the development of nonlinear optical devices, ultrashort optical pulses are an important tool, as the extremely high peak power resulting from the temporal localization of the pulse energy significantly enhances nonlinear optical effects. Further enhancement of nonlinear optical phenomena can be achieved through spatial localization of the field resulting, for example, from near-field effects in nanostructures. We have developed rigorous electromagnetic modeling tools based on the Rigorous Coupled-Wave Analysis (RCWA) and Finite-Difference Time Domain (FDTD) techniques to analyze near-field effects in optical nanostructures. Moreover, we have extended the RCWA modeling tool to analyze second-
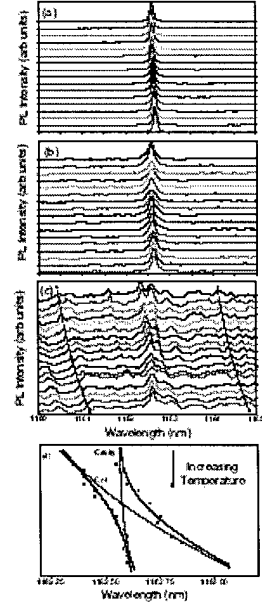

Fig. 5. Dot-nanocavity anti-crossing. In all Figs the temperature is scanned from 13K to 29 K (a)-(c) Nanocavity PL as a function of temperature and excitation power from high to low (d) The two coupled-system peaks are plotted as a functionof temperature and compared with the scan rates of an uncoupled QD (red curve) and an empty cavity (blue curve)
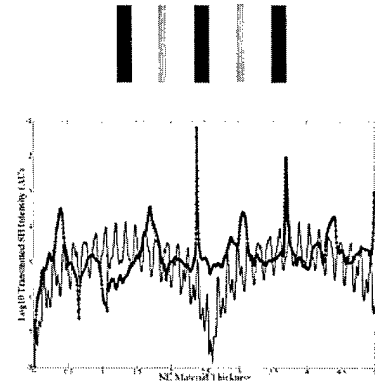
harmonic generation in nanostructures in the undepleted-pump limit. The conditions for efficient SHG are a suitable nonlinear medium, high beam intensity and phase matching. The condition for high intensity can be satisfied by utilizing near-field localization effects in a periodic medium (e.g., a light pulse passing through a properly designed periodic medium will tend to be concentrated in the high index material, provided it has the correct polarization). However, the condition of phase matching should also be satisfied. Simply speaking, phase matching implies that the propagation speed of both the pump beam and the SHG beam in the medium should be the same. In most naturally occurring materials, this is not the case, due to dispersion effects. Also, it happens that this will be even worse for the periodic medium. To circumvent this problem, a new design was developed. This innovation makes use of the fact that while the pump beam is concentrated in the high index material, the generated second harmonic is mainly propagating in the air gaps. So, if thin slabs of a third material are inserted in between the

Figure 6. Second harmonic generation in bulk material (black) and double slab periodic medium (blue).

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original periodic slabs, they will have a 'braking' effect on the second harmonic. Using a modified nonlinear version of the RCWA technique, the optimal dimensions of these secondary slabs was designed. The research results show that this method combined with the original filed localization technique, will enhance the generated second harmonic by approximately 2.5 orders of magnitude (see Fig. 6). Using these tools, we have designed several nanostructured nonlinear optical devices, and are fabricating these structures. Structural and functional characterization of the fabricated devices using nanoscale characterization methods (see below) will facilitate validation of the modeling tools, understanding of near-field optical physics in nanostructures, and design of more advanced nonlinear optical nanostructures.

9. We used RCWA technique to design 2-D photonic crystals for operation with free space modes. These 2-D photonic crystals have been used as a lattice to create single mode nanocavities for integration with quantum dots. The approach we have investigated was based on introducing an array of periodic defects (shown in red in Fig. 7a) that causes strong field localization, thereby becoming resonant for the specific design frequency. Such a structure exhibits very strong field concentration at the location of the defect (see Fig. 7c) for a very narrow range of frequencies over a large angular bandwidth (see Fig. 7b). We observed strong near-field interaction between adjacent defects that modifies the electric field in the transverse direction. Additional advantage of such a device is high field localization at the site of the defect (see Fig. 7c) that can be used for efficient detection when the defect site is constructed using a photosensitive material. The study included investigation of the period of the defect and the strength of the field localization. Incorporating quantum/nonlinear optical properties for the material used as a periodic defect of the photonic crystal has been also investigated.
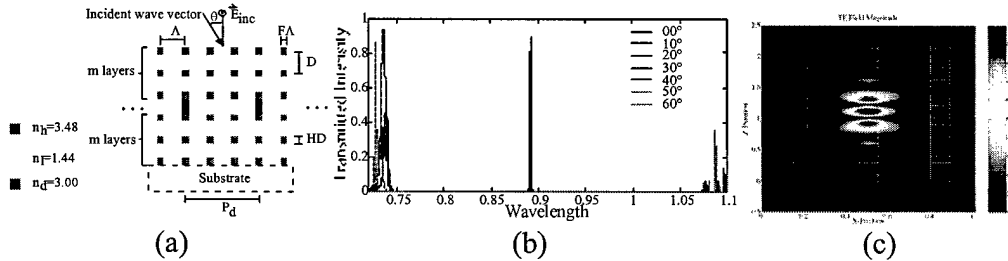

Figure 7. A 2-D artificial dielectric nanostructure with a quasi-periodic array of "defects": (a) 3 material geometry of the 2-D lattice and the periodic defects (red); (b) transmission spectrum with periodic defects; (c) optical field localization in a high index defect nanocavity.

10. To fabricate nanocavities for operation with free space modes, we also investigate growth of different material compositions to allow creating high-low dielectric nanostructures such as oxidized GaAs-AlAs (GaAs-AlO) nanostructures. We have fabricated GaAs-AlO and found an effective method to characterize the refractive index of oxidized AlAs. We investigate the optical properties of oxidized AlAs under different oxidation conditions. We have also explored the possibility of using the oxidation process to fabricate device structures that are difficult to fabricate with other processing techniques. We have also constructed and characterized a spectrometer for measurement and characterization of quantum dots at low temperature (in the range 8-20 K). This characterization system can use our femtosecond laser sources as well as

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narrow-band CW laser sources for experiments to study the decoherence time. We are in the process of setting up basic experiments for quantum dots characterization using our femtosecond scale imaging techniques.

11. We recently constructed a unique all-fiber near-field optical microscope for measurement of the complex amplitude of the near field on the nanoscale at operating wavelengths around 1.55 µm, extending its design and operation with femtosecond laser pulses and in a broad spectral range for investigation of both linear and non linear optical phenomena in the near field. The coherent NSOM is implemented with a combination of a NSOM and an interferometer
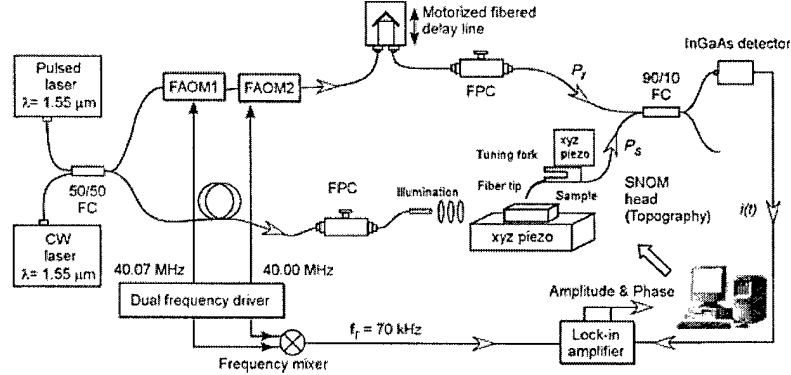

Figure 8. Set-up of the 1.55 um coherent scanning near-field optical microscope working either with CW or ultra-short pulses.

(heterodyne in our case). We use an all fiber-based system design to achieve interferometric stability and operate the system at a telecommunication wavelength in the infrared range (~1.55 µm) to meet the need in building characterization tools for better understanding nanophotonic devices for telecommunication applications. Also, our interferometric detection system can work either with CW light or ultrashort pulses. For the pulsed system, an optical delay line is used for temporal pulse correlation with τ=2 fs resolution steps. A schematic diagram of the set-up is presented in Fig. 8. The 1.55 µm laser is split to create a reference with a frequency shifted using two acousto-optic modulators. The second beam is used for illuminate in different configurations, according to the desired measurement (collection mode, illumination mode, waveguide injection collection mode). The polarization mode is adjusted using a fiber polarization controllers. A fiber tip is brought close to the surface using an atomic force microscope (AFM). The NSOM tip is mounted on a tuning fork and an electronic feedback controls the sample-tip distance within a few nanometers. The commercial AFM (Nanonics TS-2000) is composed of two flat piezoelectric scanners permitting either the tip or the sample to be moved. The light (propagating or evanescent) emerging from the structure is collected by the fiber tip. The signal and the reference beams are recombined into the InGaAs detector for post signal processing and analysis. In our experiments we first characterize our instrument with a simple structure. The waveguide core is a 5 µm by 5.3 µm doped glass (n_c= 1.56 @ 1.55µm) ridge structure, covered with a top-cladding doped glass (n_{cl}= 1.43 @ 1.55µm). Near the measuring area, a portion of the top-cladding above the waveguide (Fig. 9a and 9b) has been removed by etching process. In this case, the sample surface (above the waveguide core) has no topography and can thus avoid artifacts due to the structure. By scanning the structure surface, the fiber tip collects evanescent light emerging from the waveguide. A signal can therefore be detected only if the cross-correlation $C(\tau) = \int dt\, E_{sig}(t)E_{ref}^*(t-\tau)$ between the two pulses

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(reference and signal) is non-zero. This can be obtained by varying the relative time delay τ. The measured heterodyne signal, $i(t - \tau) \propto \cos[2\pi\Delta f \cdot (t - \tau) + \varphi(t - \tau)]$, where Δf is the beat frequency of the signal and the reference channel which is used for lock-in detection to extract the complex amplitude information, and $\varphi(t-\tau)$ is the relative phase difference between the signal and the reference. The amplitude (Fig. 9c) and phase (Fig.9d) are mapped by scanning the surface (for a fixed value of τ). By moving the relative position of the delay line (τ), the temporal position of the pulse can be mapped. The amplitude is the cross-correlation function amplitude. The phase (iso-phase lines) is linear (laterally in y) as a plane wave phase. Outside of the waveguide area, the signal-to-noise ratio is zero and the phase is therefore cannot be detected.
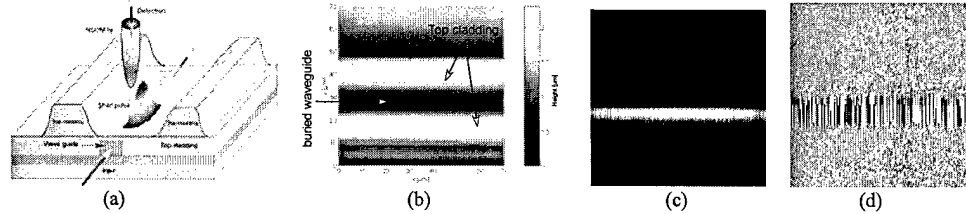

(a)   (b)   (c)   (d)

Fig. 9 Schematic diagram of the experimental structure (a) and AFM image (70 μm × 70 μm scan size) (b) of the waveguide area (top view) where a portion of the top-cladding has been partially removed. Top view of the 2-D normalized amplitude (c) and phase ([−π, π]) of the evanescent field of a femtosecond short pulse mode (70 μm × 70 μm scan size) (d).

e standard deviation of the phase depends on the inverse of the square root of the signal-to-noise ratio. By varying the delay line time τ, we can track the pulse (or more precisely the cross-correlation function) at different time and spatially. If the pulse at the reference arm were a Dirac function, the correlation function $C(\tau)$ would show the envelope of the pulse in the signal arm. However, unfortunately, this can never be the case. An analysis of both pulses before their combination in the coupler would enable extrapolation of the real shape of the pulse from the measured cross-correlation function. Figure 10 shows the evolution of the
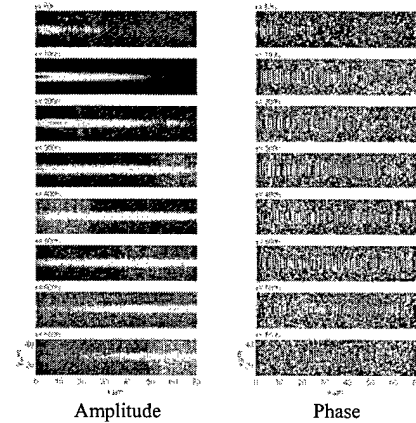

Amplitude   Phase

Fig. 10 Spatial (x, y) and temporal tracking of the short pulse normalized amplitude (a.u.) and phase ([−π, π]) in the waveguide in function of the time delay τ (from 50 fs to 650 fs).
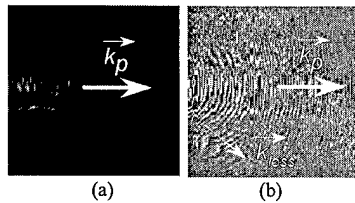

(a)   (b)

Figure 11 Losses occurring in a waveguide. Amplitude (a) and phase (b) of a short-pulse.

"pulse envelope" in the waveguide. Fig. 11 shows the propagation loss in a standard waveguide. The phase, which is the best representation of the light propagation (k_p-vector), shows clearly the losses that can occur outside the waveguide (k_{loss}-vector) (Fig. 11b).

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4. Personnel Supported

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28. M. P. Nezhad, K. Tetz, and Y. Fainman,"Gain assisted propagation of surface plasmon polaritons on planar metallic waveguides," Opt. Express 12, 4072-4079 (2004)

29. M. A. Alvarez-Cabanillas, F. Xu, Y. Fainman, "Modeling microlenses by use of vectorial field rays and diffraction integrals," Applied Optics, vol.43, no.11, pp.2242-50, 2004.

30. W. Nakagawa, Y. Fainman, "Tunable optical nanocavity based on modulation of near-field coupling between subwavelength periodic nanostructures," IEEE Journal of Selected Topics in Quantum Electronics, vol.10, no.3, pp.478-83, 2004.

31. C-H. Chen, K. Tetz, W. Nakagawa, and Y. Fainman, "Wide Field of View GaAs/Al$_x$O$_y$ 1-D Photonic Crystal (PC) Filter," Applied Optics (in press).

32. U. Levy and Y. Fainman, "Dispersion properties of inhomogeneous nanostructures," J. Opt. Soc. Am. A., 21, 881-889 (2004).

33. U. Levy, C. H. Tsai, L. Pang and Y. Fainman, "Engineering space-variant inhomogeneous media for polarization control," Opt. Lett., 29, 1718-1720 (2004).

34. U. Levy, C. H. Tsai, H. C. Kim and Y. Fainman, "Design, fabrication and characterization of subwavelength computer-generated holograms for spot array generation," Accepted for publication in Opt. Express

35. U. Levy, M. Nezhad, H. C. Kim, C. H. Tsai, L. Pang and Y. Fainman, "Implementation of graded index medium using subwavelength structures with graded fill factor," Accepted for publication in J. Opt. Soc. Am. A.

36. K Campbell, A. Groisman, U. Levy, L. Pang, S.hayan Mookherjea D. Psaltis and Y. Fainman, "A microfluidic 2×2 optical switch," Accepted for publication in Applied Physics Letters

37. R. E. Saperstein, D. Panasenko, Y. Fainman, ""Demonstration of a microwave spectrum analyzer based on time-domain optical processing in fiber" Opt. Lett. **29,** 501-503 (2004).

38. L.Pang, Y.-M Shen, K. Tetz and Y. Fainman, 'PMMA quantum dots composites fabricated via use of pre-polymerization', submitted to Optical express

13

39. L. Pang, M. Nezhad, U. Levy, C.-H. Tsai, and Y. Fainman, 'Form birefringence structure fabrication in GaAs by use of SU-8 as dry etching mask', accepted by Applied Optics

40. K. Tetz, Y. Fainman, "Excitation and Direct Imaging of Surface Plasmon Polariton Modes in a Two-dimensional Grating" submitted to Applied Physics Letters.

6. Interactions/transitions

a. Meetings, Conferences, Seminars, Proceedings

1. W. Nakagawa, C.-H. Chen, C.-H. Tsai, P.-C. Sun, and Y. Fainman, "Angularly insensitive wavelength filters using photoni crystal nanocavities," in OSA *Trends in Optics and Photonics (TOPS) Vol. 57, Quantum Electronics and Laser Science Conference (QELS 2001),* Technical Digest, Postconference Edition (Optical Society of America, Washington DC, 2001), pp. 169–170.

2. Y. Fainman, "Nonlinear femtosecond information processing systems," presented at the Euro-American Workshop on Optoelectronic Information Processing, Valencia (Spain), May 28-30, 2001; also to appeared in the Critical review of SPIE, Optoelectronic Information Processing, B. Javidy and P. Refregier, ed., 2001. **(Invited)**

3. C. H. Chen, W. Nakagawa, P. C. Sun, Y. Fainman, "Design of wide-angular-bandwidth filter based on multiple cavity 1-D photonic crystal," presented at the 2001 OSA/ILS XVII Annual Meeting, Long Beach, California, 2001.

4. D. Panasenko, and Y. Fainman, "Single-shot interferometric autocorrelation of femtosecond pulses using two photon conductivity in a silicon CCD," presented at the 2001 OSA/ILS XVII Annual Meeting, Long Beach, California, 2001.

5. G. Klemens, W. Nakagawa, R. C. Tyan, and Y. Fainman, "Phase matching in anisotropic form-birefringent nanostructures," presented at the 2001 OSA/ILS XVII Annual Meeting, Long Beach, California, 2001.

6. N. Alic and Y. Fainman, " Fast split step Fourier method in optical fibers, presented at the 2001 OSA/ILS XVII Annual Meeting, Long Beach, California, 2001.

7. W. Nakagawa, G. Klemens, and Y. Fainman, "Enhanced second-harmonic generation in periodic nonlinear optical nanostructures," presented at the the 14-th IEEE/LEOS 2001 Annual Meeting, November 11-15, La Jolla, California, 2001

8. R. Liu, C. H. Tsai, Y. Fainman, T. Schmedake, M. Sailor, " Porous silicon vapor sensor based on polarization interferometry," presented at the the 14-th IEEE/LEOS 2001 Annual Meeting, November 11-15, La Jolla, California, 2001

9. Y. Fainman, D. Panasenko, R. Rokitski, D. Marom, Y. Mazurenko, and P. C. Sun, "Nonlinear space-time processing," presented at the the 14-th IEEE/LEOS 2001 Annual Meeting, November 11-15, La Jolla, California, 2001 (**Invited**).

10. D. Panasenko and Y. Fainman, "Single-shot interferometric correlator for ultrashort laser pulses based on noinlinear absorption in a silicon CCD," presented at the the 14-th IEEE/LEOS 2001 Annual Meeting, November 11-15, La Jolla, California, 2001.

11. D. Panasenko, R. Rokitski, D. M. Marom, Y. Mazurenko, P.-C. Sun, N. Alic and Y. Fainman. *"Nonlinear optical information processing with femtosecond pulses"*, presented at 2002 SPIE AeroSense meeting, paper 4737-7

12. Y. Fainman, "Ultrafast information processing with optical nonlinearities," presented at Photonics-Asia SPIE conference, Shanghai, China, October 14-18, 2003, (**Invited**)

13. K Tetz, Chyong-Hua Chen, W Nakagawa, HH Wieder, Y Fainman. Design, fabrication and characterization of narrowband angularly-insensitive resonant cavity filter. LEOS 2002. 2002 IEEE/LEOS Annual Meeting Conference Proceedings. 15th Annual Meeting of the IEEE Lasers and Electro-Optics Society (Cat. No.02CH37369). IEEE. Part vol.2, 2002, pp.449-50 vol.2. Piscataway, NJ, USA

14. Y Fainman, W, Nakagawa C-H Tsai, C-H Chen, G Klemens. Nanophotonic materials and devices for optical system integration. LEOS 2002. 2002 IEEE/LEOS Annual Meeting Conference Proceedings. 15th Annual Meeting of the IEEE Lasers and Electro-Optics Society (Cat. No.02CH37369). IEEE. Part vol.2, 2002, pp.651-2 vol.2. Piscataway, NJ, USA (**Invited**).

15. Y. Fainman, " Nanophotonic materials and devices," Photonics West, SPIE Conference, San Jose, ,January 25-29, 2003. (**Invited**)

16. Y. Fainman, "Ultrafast Information Processing with Optical Nonlinearities," CLEO/QELS, June 1-6, 2003, Baltimore, Maryland, , (**Tutorial**)

17. Y. Fainman, D. Panasenko, R. Rokitski, D. Marom, K. Oba, Y. Mazurenko, and P. C. Sun, "Ultrafast Information Processing with Optical Nonlinearities," presented at Optics in Computing conference, Washington, DC, June 18-20, 2003. Optics in Computing (Trends in Optics and Photonics Series Vol.90). Optical Soc. of America. 2003, pp.100-2. (**Invited**)

18. Y. Fainman, " Nanophotonic Materials and Devices for Optical System Integration," DARPA Topical Meeting on Optical Photonic Bandgap Research, January 22-23, 2003. (**Invited**)

19. L. Pang, W. Nakagawa, C.-H. Tsai, and Y. Fainman, 'Fabrication of 2D photonic crystal using multiple exposures', Proc. SPIE 5181, 223 (2003)

20. M. P. Nezhad, C. Tsai, L. Pang, W. Nakagawa, G. Klemens, and Y. Fainman , "Form birefringent retardation plates in GaAs substrates: design, fabrication, and characterization",

Proc. of SPIE, vol. 5225, Nano- and Micro-Optics for Information Systems, Louay A. Eldada, Editor, October 2003, pp. 69-77

21. Nesci A, Fainman Y. Complex amplitude of an ultrashort pulse with femtosecond resolution in a waveguide using a coherent NSOM at 1550 nm. [Conference Paper] SPIE-Int. Soc. Opt. Eng. Proceedings of Spie - the International Society for Optical Engineering, vol.5181, no.1, 2003, pp.62-9.

22. Panasenko D, Rokitski R, Alic N, Marom DM, Mazurenko YT, Pang Chen Sun, Fainman Y. Real-time synthesis and detection of ultrafast optical waveform. [Conference Paper] SPIE-Int. Soc. Opt. Eng. Proceedings of Spie - the International Society for Optical Engineering, vol.4978, no.1, 2003, pp.58-69. **(Invited)**

23. C. H. Tsai, U. Levy, L. Pang, Y. Fainman, "Fabrication and characterization of GaAs-based space-variant inhomogeneous media for polarization control at 10.6um", Proc. SPIE, Nanoengineering: Fabrication, Properties, Optics, and Devices, Vol.5515, pp.142-149 (2004)

24. R. E. Saperstein, D. Panasenko, Y. Fainman, "Demonstration of a RF-photonic spectrum analyzer using ultrafast optical pulses," in Technical Digest of 2003 Frontiers in Optics, The 87th OSA Annual Meeting and Exhibit (Omnipress, 2003), Session WII4

25. R. E. Saperstein, D. Panasenko, Y. Fainman, "Demonstration of a microwave spectrum analyzer using time-domain processing in optical fibers" in 2003 IEEE LEOS Annual Meeting Conference Proceedings (IEEE, Piscataway, NJ, 2003), 931-932

26. Fainman Y, Panasenko D, Rokitski R, Saperstein R, Marom DM, Mazurenko YT, Sun PC. Applications of optical nonlinearities for signal processing. [Conference Paper] 2003 IEEE LEOS Annual Meeting Conference Proceedings (IEEE Cat. No.03CH37460). IEEE. Part vol.1, 2003, pp.262-3 vol.1. Piscataway, NJ, USA.**(Invited)**

27. Nesci A, Fainman Y. Complex amplitude of an ultrashort pulse in a waveguide measured with a coherent, femtosecond resolution NSOM at 1550 nm. [Conference Paper] 2003 IEEE LEOS Annual Meeting Conference Proceedings (IEEE Cat. No.03CH37460). IEEE. Part vol.1, 2003, pp.49-50 vol.1. Piscataway, NJ

28. Ambs P, Bigue L, Fainman Y, Binet R, Collineau J, Lehureau J-C, Huignard J-P. Image reconstruction using electrooptic holography. [Conference Paper] 2003 IEEE LEOS Annual Meeting Conference Proceedings (IEEE Cat. No.03CH37460). IEEE. Part vol.1, 2003, pp.179-80 vol.1. Piscataway, NJ, USA.**(Invited)**

29. Nakagawa W, Tetz K, Fainman Y. Design of near-field optical nanostructures for enhanced second-harmonic generation. [Conference Paper] Quantum Electronics and Laser Science (QELS). Postconference Digest (IEEE Cat No.CH37420-TBR). Optical Soc. of America. 2003, pp.2 pp.. Washington, DC

30. Y. Fainman," Ultrafast Signal Processing using optical nonlinearities," Optics in Computing, Switzerland, April 2004.**(Invited)**

31. Levy U, Chia-Ho Tsai, Nezhad M, Nakagawa W, Chen C-H, Tetz KA, Pang L, **Fainman** Y. Nanophotonics: materials and devices. [Conference Paper] SPIE-Int. Soc. Opt. Eng. Proceedings of Spie - the International Society for Optical Engineering, vol.5359, no.1, 6 July 2004, pp.126-44. USA

32. R. E. Saperstein, N. Alic, D. Panasenko, R. Rokitski, Y. Fainman, "Time-Domain Optical Processing using Chromatic Dispersion for Ultrashort Pulse Shaping" presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico

33. M. P. Nezhad, K. Tetz, U. Levy and Y. Fainman "Propagation of Surface Plasmon Polaritons on the Boundary of a Metal and a Gain Medium," presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico

34. K. Tetz, R. Rokitski , M. P. Nezhad , and Y. Fainman, "Excitation and Direct Imaging of Surface Plasmon Polariton Modes in the Near-Infrared," presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico

35. Y. Fainman, " Nanophotonics for optoelectronic systems integration," presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico **(Invited)**

36. Y. Fainman, "Signal processing, imaging and cryptography with ultrashort laser pulses," presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico **(Invited)**

37. L. Pang, U. Levy, K. Campbell, A. Groisman, S. Mookherjea, D. Psaltis, and Y. Fainman, " A microfluidic 2x2 switch," presented at 2004 IEEE LEOS Annual Meeting, Nov. 7-11, 2004 Rio Mar, Puerto Rico

38. R. Rokitski, K. Tetz, and Y., Fainman, " Ultrashort plasmon-polariton excitation and imaging, presented at 2004 IEEE LEOS Annual Meeting, November 7-11, 2004 (Postdeadline paper)

b. Consultative and advisory functions

1. Y. Fainman, W. Nakagawa, G. Klemens, C.-H. Chen, C.-H. Tsai, K. Tetz, " Nanophotonics," presented at the 2001 DARPA-NSF-OIDA Forum 2001, Washington DC, .November 28, 2001,

2. Y. Fainman, L. Sham, A. Scherer, and C. Tu, "Quantum device technologies – applying 2-D photonic crystals," QuIST DARPA kickoff meeting,, Dallas, Texas, November 25-29, 2001,

3. Y. Fainman, NSF Review Pannel on Nanophotonics, NSF, Washington, DC, November 29, 2001

4. Y. Fainman, "Nanophotonics," The Nano-technology Forum, Ramat Aviv, Israel, December 10-11, 2001

5. Y. Fainman - Guest Editor for the JOSA: B special issue on "Innovative Physical Approaches to the Temporal or Spectral Control of Optical Signals" 2001 (joint with Dr. Mossberg and Dr. Kitayama

6. Y. Fainman - Guest Editor for the Journal on Optical Memory and Neural Networks special issue on "Ultrafast Optics" 2001

7. Y. Fainman, L. Sham, A. Scherer, and C. Tu, "Quantum device technologies – applying 2-D photonic crystals,Colloquium on Physics of Quantum Electronics, Snowbird, Co, January 7-10, 2002

8. Y. Fainman, "Real-time spatial-temporal signal processing with optical nonlinearities," Seminar, ECE Dept., UC-Davis, April 17, 2002

9. Y. Fainman, P. Yu, "RF spectrum analyser," OASP DARPA kick-off meeting, San Diego, California, August 7-8, 2002

10. Y. Fainman, STAB DARPA Review Meeting, August 13, 2002

11. Y. Fainman, "OptIPuter Program", NSF, Advisory Board, August 19, San Diego, 2002

12. Y. Fainman, L. Sham, A. Scherer, and C. Tu, "Quantum device technologies – applying 2-D photonic crystals," QuIST DARPA Review meeting, Cambridge, Massachusets, September 9-12, 2002

13. Y. Fainman, "Optical CDMA", NSF workshop on optical Networks, October 21-22, 2002, Washington, DC

14. Y. Fainman, "Nanophotonics," DARPA Workshop on Photonic Crystals, January 22-23, 2003, San Diego, SPAWAR

15. Y. Fainman, " Research Directions in Photonics," ON*VECTOR Photonics Workshop-NTT, San Diego, February 3-4, 2003

16. Y. Fainman, "Why Optical Signal Processing?," DARPA DSRC Workshop, Washington, DC, February 20-21, 2003

17. Y. Fainman, NSF Review Pannel on Nanophotonics, NSF, Washington, DC, April, 2003

18. Y. Fainman, STAB DARPA Final Report Meeting, September 24, 2003

19. Y. Fainman, NSF Career Review, NSF, Washington, DC, October 30-31, 2003

20. Y. Fainman - Guest Editor for the JOSA: B special issue on "Innovative Physical Approaches to the Temporal or Spectral Control of Optical Signals" 2002 (joint with Dr. Mossberg and Dr. Kitayama

21. Y. Fainman - Guest Editor for the Journal on Optical Memory and Neural Networks special issue on "Ultrafast Optics" 2002

22. Y. Fainman, " Nanophotonic Materials and Devices for Optical System Integration," DARPA Topical Meeting on Optical Photonic Bandgap Research, January 22-23, 2003. **(Invited)**

23. Y. Fainman, " Research in Photonics," ON*VECTOR Photonics Workshop, San Diego, February 3-4, 2003**(Invited)**

24. Y. Fainman, L. Sham, A. Scherer, and C. Tu "2-D photonic crystal nanocavities for quantum information processing," DARPA QuIST Program review, Los Angeles, June 23-25, 2003

25. "Quantum device technologies – applying 2-D photonic crystals," DARPA QuIST PIs Review Conference, November 12-14, 2003, Fort Lauderdale, Florida

26. "Quantum device technologies – applying 2-D photonic crystals," DARPA QuIST PIs Review Conference, November 16-19, 2004, Scotsdasle, Arizona

7. New discoveries: None

8. Honors/Awards: None
C.W. Tu was elected Fellow of the IEEE, January 2002
Y. Fainman was elected Fellow of the IEEE, January 2003
C.W. Tu was elected Fellow of the AVS, 2004
Y. Fainman was elected Fellow of the SPIE, 2004.